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FRAMEWORK FOR HOLISTIC SUSTAINABLE DISASTER RECOVERY

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Abstract: The recent disastrous events (Fort McMurray wildfire, Hurricane Matthew, etc.) stress the dire need for a proactive decision making framework for holistic sustainable disaster recovery. Such tool should highlight the redevelopment strategies that meet the needs of the stakeholders while decreasing the built environment's vulnerabilities. This paper presents such framework through an innovative approach that involves: (1) a multi agent-based modeling approach to capture the participating entities needs and decision actions, (2) well-established community specific vulnerability indicators to evaluate the built environment vulnerability, and (3) multi-objective evaluation approach to simultaneously meet the communities' recovery and vulnerability reduction needs. Accordingly, the proposed framework can identify the optimal redevelopment strategies at the community level. To evaluate its potentials, the proposed framework was implemented on the post-Katrina recovery processes in two Mississippi coastal counties regarding the residential and economic sectors. The developed model utilized the actual recovery strategies and plans employed by the Mississippi Development Authority (MDA). The model attempted to optimize the associated government agency's budget distribution over the different recovery plans to: (1) increase the welfare of the impacted stakeholders, and (2) decrease the built environment vulnerability. The framework's outcome dominated the actual budget distribution by the MDA regarding the recovery progress of the stakeholders and the host community's vulnerability. Such novel approach will enable the decision makers to engage their communities in the prevent-event phases to find the common shared goals that decrease the built environment vulnerability and achieve true sustainability post a disastrous event.

1 INTRODUCTION

The world has seen an increasing number of natural disasters throughout the last decade (Eid and El-adaway 2017). This led to interdisciplinary studies that aim to optimize the disaster recovery efforts to maximize the potential outcomes of the redevelopment projects. Disaster recovery is defined as non-linear actions and processes that are driven by the broad community stakeholders, in which the outcomes are multi-dimensional, affecting the livelihood of the built environment, and ultimately aim to decrease the vulnerability of the host communities to future hazards (Chang 2010, Ingram 2007, Smith and Wenger 2007, Sullivan 2003, Mileti 1999). In order to achieve sustainable disaster recovery, decision makers need to: (1) maximize the individual utility functions of the local community stakeholders, and (2) decrease the built environment social, economic, and environmental vulnerability.

To maximize the utility functions of the local residential and the economic sectors, decision makers need to involve them into the planning phases of the recovery processes (Eid and El-adaway 2016a, Boz and El-adaway 2014, National Disaster Recovery Framework 2011). Recent case studies of disaster recovery world wide confirmed that the assimilation of the stakeholders in the planning phases increases the approval rate of the recovery projects by the local communities (Olshansky et al. 2006). This also increases the collective welfare of the society. To this end, the US National Disaster Recover Framework (NDRF) recommended the integration and participation of the broad community in the planning of disaster recovery strategies to achieve sustainable recovery projects (NDRF 2011). Nonetheless, the literature still lacks comprehensive decision making frameworks that assimilate the stakeholders of the host community in the planning of the disaster recovery projects. (Eid and El-adaway 2016b). On the other hand, to ensure sustainable disaster recovery, the redevelopment projects should aim to decrease the vulnerability of the built environment (Ingram et al. 2006). This approach will decrease the host communities' potential losses to hazards (Eid and El-adaway 2016a). Recent research investigated the three dimensions of vulnerability; social, economic, and environmental, and how the different community-specific factors affect them (Burton 2012, Cutter et al. 2006, Pratt et al. 2004). Vulnerability is generally defined as the likelihood that an individual or group of individuals will be exposed to adverse effects by a hazardous event (Cutter 1993). To evaluate the vulnerability of the built environment based on the community-specific data, various vulnerability indicators were developed. Such indicators are categorized into; Social, Social Vulnerability Index (Cutter et al. 2003); environmental; Environmental Vulnerability Index (Pratt et al. 2004); and economic, Economic Resilience to Natural Hazard (Burton 2010). However, there is still absence of integration of the different vulnerability indicators into a comprehensive decision making framework that aims to develop holistic disaster recovery strategies.

1.1 Knowledge gap, goals, and objectives

The developed disaster recovery models found in literature focus on optimizing the reconstruction of isolated projects rather than a community-level, multi-dimensional development (Eid and El-adaway 2016a). Such models utilized tools ranging from dynamic programming to evolutionary optimization techniques (El-Anwar et al. 2010, Pradham et al. 2007, Kweku-Muata et al. 2002). Those tools are not suitable to account for the heterogeneous needs of the host community stakeholders, as addressed by the NDRF recommendations. Moreover, the developed models did not adequately address the vulnerability reduction of the host community based on the redevelopment activities. This research aims to fill in the current knowledge gap through presenting a framework that identifies optimal disaster recovery strategies, via a novel holistic approach. This will be carried out through a bottom-up approach that integrates the broad community stakeholders into the decision-making processes. Also, the framework will account for the three-dimensional vulnerability of the built environment through integrating them into the objective functions of the government agency. The ultimate goal of this framework is to better guide the disaster recovery strategies at the government level to increase the overall welfare of the impacted communities.

2 METHODOLOGY

The authors developed the following three step research methodology:(1) model the objectives, strategies, and learning behaviors of the associated stakeholders; (2) implement well-established community-specific vulnerability assessment tools, and (3) interpret and analyze the results generated from the developed multi-objective simulation model.

3 MODEL DEVELOPMENT

3.1 Vulnerability assessment tools

Vulnerability is the potential of loss of an individual or group of individuals due to their inherent attributes and exposure to hazardous events (Eid and El-adaway 2016b, Burton 2012, Cutter et al.1993, Mitchell 1989). Accordingly, the proposed model needs to evaluate the social, economic, and environmental vulnerability of the built environment based on the community-specific data. This will enable for comprehensive integration of the indicators into the decision-making processes. The following sub-sections illustrates the utilized vulnerability assessment tools across the three dimensions.

3.1.1 Social vulnerability

The Social Vulnerability Index (SoVI) developed by Cutter et al. (2003) is utilized to evaluate the built environment social vulnerability. SoVI is one of the well-recognized vulnerability indicators within the social science field (Burton 2012). SoVI evaluates the community relative vulnerability based on their socioeconomic data. The indicator utilizes Factor Analysis (FA) to depict the factors that impact the social vulnerability. Through scoring those factors, a relative vulnerability score for each region understudy can be calculated. The scores are affected by any changes within the socioeconomic data of the built environment due to the disaster impact or the recovery process.

3.1.2 Economic vulnerability

The authors utilized the methodology developed by Burton (2010) to evaluate the economic vulnerability of the built environment. The Economic Vulnerability Index (EconVI) evaluates the micro (individual) and meso (regional) economic vulnerability of the host community based on their socioeconomic data. Similar to the SoVI, EconVI utilizes FA to determine the factors that governs the economic vulnerability of the regions understudy. EconVI also scores the relative vulnerability of each region based on the FA factors, that will change due to the disaster impact and the recovery activities.

3.1.3 Environmental vulnerability

The presented framework utilizes the comprehensive community-specific Environmental Vulnerability Index (EVI) developed by the South Pacific Applied Geoscience Commission. The EVI evaluates the environmental vulnerability of the community based on their environmental data. EVI maps each of its 50 indicators on pre-defined scales ranging from 1 to 7 (least to most vulnerable). Thus, an average EVI score can be calculated based on the scores of the 50 indicators. For further details on the SoVI, EconVI, and EVI methodologies, see Eid and El-adaway (2017, 2016a, and 2016b).

3.2 Disaster recovery bottom-up modeling approach

To assimilate the needs of the broad community stakeholders into the decision-making process, the authors utilized Agent Based Modeling (ABM). ABM enables the representation of the different stakeholders via individual agents in a root-to-grass approach. This enables the evaluation of the stakeholders' welfare post a disastrous event, and simulate how they recover. Such approach will meet the recommendations made by the NDRF. ABM also enables study of emerging behavior of the society to different shocks and perturbations (Eid and El-adaway 2016b). ABM was utilized in different emergency management studies; residential evacuations, flood risk and emergency management, humanitarian assistance, etc. (Crooks and Wise 2013, Park et al. 2012, Miles and Chang 2006). The developed ABM depicts three main entities in the recovery process; residents, economic sectors, and the government agencies. As per the NDRF (2011), the government agencies are responsible for aiding the impact communities through various disaster recovery strategies. This requires prioritizing some of the strategies over the others depending on the needs of the community and the overall impact of each strategy.

Figure 1 presents an overview on the developed ABM. In the event of a natural disaster, each resident and economic agent evaluates the structural losses imposed on its structure. The agents then evaluate the repair costs, and apply for assistance from the government agent. The government assistance determines the recovery progress of each agent as well as its decision on leaving the impacted region. The government agent thus manages the funding proportion across the different recovery plans to maximize the individual utility function for the local community. The recovery plans should also decrease the built environment three-dimensional vulnerability. The following sub-sections details the objective functions and learning behavior of the three agents.

3.2.1 Resident agent

The resident agent represents homeowners impacted by a disastrous event. Each agent is initiated with its own household value and income, that depicts an actual household in the host community. The objective of the resident agent is to maintain and increase their wealth by recovering and increasing the value of the household at minimum cost. Eq. 1 illustrate the objective function of the resident agent, where, i is the resident index, Z_i is the objective function of resident i, H_i is the household value, I_i is the monthly income, T_i is monthly distributed tax amount, and R_i is the monthly self-paid repair costs.

[1] $$Z_i = H_i + I_i - T_i - R_i$$

The resident agent applies for assistance if the household is damaged. The agent chooses the recovery plan that would increase its expected utility function, as seen in Eq. 2, where $E\left[U_j\right]_i$ is the expected utility of plan j, G and A are the government maximum award and average acceptance probability for plan j

[2] $\mathrm{E}\left[\mathrm{U_j}\right]_\mathrm{i} = \mathrm{Z_i} + \mathrm{G_j} \times \mathrm{A_j}$

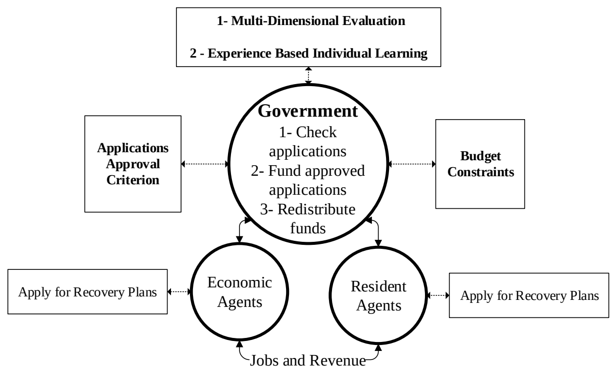


Figure 1: Agent Based Model Overview

3.2.2 Economic agent

The business sector is a crucial entity within the society. It provides goods and services, provide employment, and pay taxes. The economic agent represents the business sector within the community. Such agent will be affected by the disaster impact and the recovery process. This is manifested through the monthly revenue of the agent, as shown in Eq. 3. The income of the economic agent is driven by the residents' income and the needs for services or goods (γ), as shown in Eq. 4, where; d is the goods or services provided by this economic agent e. E is the monthly income, CT is the monthly expenses for service d, γ is the percentage of the income I used monthly by resident i to purchase goods/services d. When a disastrous event impacts a community, a perturbation in the economic agent's revenue will occur. The economic agent may sellout the business and leave the impacted region due to the physical structural losses. If the recovery cost is greater than the sellout option, the economic agent will leave the impacted community (Eid and El-adaway 2016b). Such decision is modeled in Eq. 5 and Eq. 6.

[3] $\mathrm{Revenue_d} = \sum_\mathrm{i}^\mathrm{I} \mathrm{E_{i_d}} \quad - \mathrm{EXP_d} \qquad \forall \mathrm{d} \in \mathrm{D}$

[4] $\mathrm{E_{i_d}} = \mathrm{I_i} \times \gamma_\mathrm{d} \qquad \forall \mathrm{d} \in \mathrm{D}, \forall \mathrm{i} \in \mathrm{I}$

[5] $\mathrm{RecoveryCost_e} = \mathrm{St_e} \times \sigma_\mathrm{e} - \mathrm{C_{e(n.m)}} - \mathrm{F_e}$

[6] $\mathrm{SellOut_e} = \mathrm{St_e} \times (1 - \sigma_\mathrm{e})$

3.2.3 Government agent

The objective of the government agent is to: (1) increase the welfare of the local community (Eq. 7, and 8), and (2) decrease the built environment social, economic, and environmental vulnerability (Eq. 9-11), where, ΔZ_i is the change in the resident's i objective function when applying for plan k, ΔFR_e is the change in financial recovery for economic agent e, SoVI, EVI, and EconVI are the social, environmental, and economic vulnerability indices, respectively, corresponding to agents applying for plan k. The government agent needs to optimize the budget distribution across the different disaster recovery plans to achieve the its objectives. Accordingly, the government agent requires a multi-dimensional evaluation module to assess the impact of each disaster recovery plans on the different objective functions. Such evaluation approach can then be integrated into the agent's learning module that aims to achieve its objectives.

[7] $\sum_\mathrm{i}^\mathrm{I} \Delta \mathrm{Z_{i_k}} \qquad \forall\, \mathrm{k} = 1,2, \ldots, \mathrm{K}$

[8] $\sum_{e}^{E} \Delta FR_{e_k}$ $\forall\, k = 1,2,\ldots,K$

[9] $\sum_{i}^{I} SoVI_{i_k} + \sum_{e}^{E} SoVI_{e_k}$ $\forall\, k = 1,2,\ldots,K$

[10] $\sum_{i}^{I} EconVI_{i_k} + \sum_{e}^{E} EconVI_{e_k}$ $\forall\, k = 1,2,\ldots,K$

[11] $\sum_{i}^{I} EVI_{i_k} + \sum_{e}^{E} EVI_{e_k}$ $\forall\, k = 1,2,\ldots,K$

3.2.3.1 Multi-dimensional evaluation module – Pareto Front Sorting

Pareto optimal solutions are those that no other solution can improve their outcomes without compromising one of the objective functions. Pareto Front Sorting (PFS) can then be used to sort the different solutions (plans) into fronts depending on their associated outcome, where the first front has the most positive impact on the government objective functions. Such approach will enable equal and fair comparison between the different plans across the five objectives regardless of their measuring.

3.2.3.2 Individual learning model – Roth Erev Reactive Reinforcement Learning

The government agent utilizes an individual learning module that simulates the government learning through its own experience. This will prioritize the disaster recovery plans that positively impact the community. Roth Erev model was used to simulate such process. Through calculating the rank for each plan, as shown above, an immediate reward (IR) will be given to each recovery plan which is equal to the inverse of the rank. Such value will impact the utilized action propensity (q), as seen in Eq. (12). The propensity changes with each time step given the immediate reward value, the forgetting parameter (ϕ), and the experimenting parameter (ε). Those parameters allow the government agent to explore the solution space while allowing for information exploration and exploitation (Eid and El-adaway 2016b). The probability of utilizing each plan (share of the total budget) is governed by Eq. (13), where qk(t) is the propensity of plan k in time t, ϕ and ε are the forgetting and experimenting parameters, respectively, IRk is the immediate reward, and p is the updated budget share for plan k, at time (t).

[12] $q_k(t+1) = q_k(t)[1-\phi] + IR_k \times (1-\varepsilon)$ $\forall\, k = 1,2,\ldots,K$

[13] $p_k(t) = q_k(t) / \sum_{k=1}^{K} q_k(t)$ $\forall\, k = 1,2,\ldots,K$

4 CASE STUDY

The proposed model was implemented on the post-Katrina recovery in Mississippi. The implementation scope focused on two coastal counties; Hancock and Harrison. The data required for the model initial conditions and the model outcome comparison was collected via the US Census Bureau, ReferenceUSA, and the National Land Cover Databased for years 2000-2012. The authors gathered the recovery action plans utilized by the MDA for years 2007-2015. Such plan consists of: Homeowner Assistance, a financial aid to homeowners to repair; Public Home Assistance, building poor income houses; Elevation Grant, increasing households' resilient; and Small Business Loans, loans to repair and recover. Each plan would affect the recovery progress of the stakeholders and the different socioeconomic variables within the community. Such variables impact the three-dimensional vulnerability of the community. The model's outcome is compared to the existing conditions and an actual budget distribution simulation.

5 RESULTS

5.1 Government agent budget distribution

Figure 2 illustrates a comparison between the actual budget distribution utilized by the MDA and the model outcome. The MDA budget was dominated by the Homeowner Assistance plan. This plan attempted to aid the impacted residents. However, it did not focus on the needs of the poor income households that contributes to more than 15% of the population. Meanwhile, the Public Home Assistance plan would contribute to the poor income households' recovery, and decrease the social vulnerability of the host community. The proposed model provided an evolved budget distribution that balances between the needs of the community and the vulnerability of the built environment. The government agent increased the Homeowner Assistance plan to 35% in the first two years. This provided financial support for repairing the impacted household. The government agent maintained a 20% of the budget to the Public Home Assistance plan to aid the poor income families. However, as this plan requires building new homes, it will increase the environmental vulnerability due to vegetation cover reduction. Therefore, this plan did not over dominate the other plans. On the other hand, the government agent increased the Elevation Grant share of the budget. Such plan increases the household value through making it more flood resilient. Such recovery plan will impact the social vulnerability and does not have negative impact on the environment. As such the Elevation Grant share of the budget reached 45% of the total budget by the beginning of the second half of the simulation. Finally, the government agent maintained a 20% of the budget to the Small Business Loan plan to incentivize the economic sector to stay in the impacted region and decrease the economic vulnerability due to perturbations. Such budget distribution affects the recovery of the host community, and decreases the vulnerability of the built environment as discussed in the following sections.

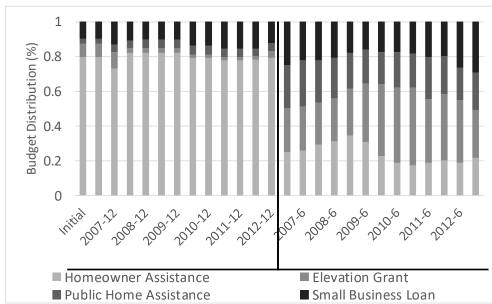


Figure 2: Government Budget Distribution

5.2 Social vulnerability

Figure 3 illustrates the existing social vulnerability conditions per county. It can be noticed that Harrison County (the most populated region) had a steady increase in its social vulnerability. This is mainly contributed to the lack of utilizing the Public Home Assistance and Elevation Grants by the MDA. Figure 4 presents the social vulnerability per county for the actual budget distribution simulation utilizing the developed model. Such simulation mimics the MDA budget to allow for fair comparison between the proposed framework outcome and actual action utilized by the MDA. Figure 4 does not show the same exact numbers as Figure 3, as social variables can not be replicated (Eid and El-adaway 2017), yet both show the same trajectory of social vulnerability per county. The proposed model decreased the social vulnerability across the two counties, as shown in Figure 5. The proposed framework decrease the social vulnerability of Harrison County with a SoVI score of 1.902 in comparison to the 3.213 and 2.755 for the existing conditions and actual budget distribution simulation, respectively. Such reduction is due to integrating the SoVI into the decision-making processes of the government agent. Such approach guided the redevelopment activities to decrease the vulnerability of the most populated regions. The proposed model proved minimal impact on Hancock County (least populated region).

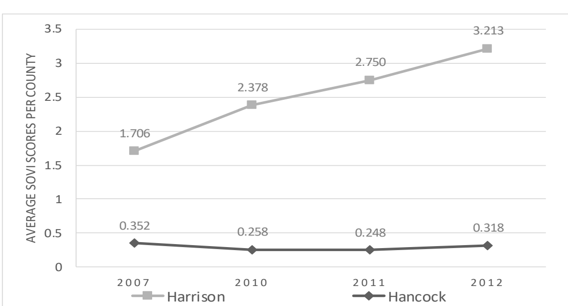


Figure 3: Existing Social Vulnerability

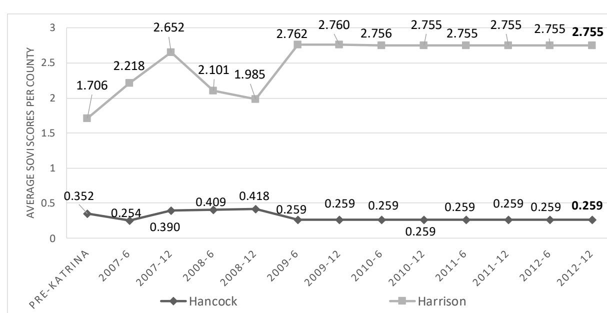


Figure 4: Actual Budget Distribution Social Vulnerability

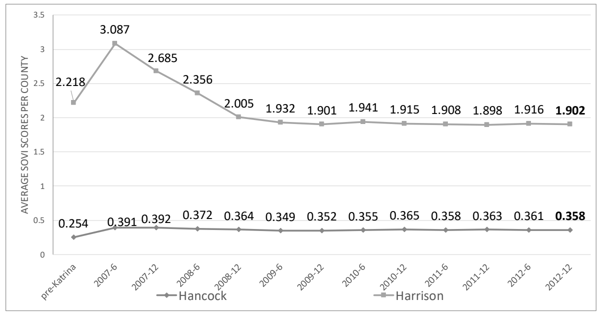
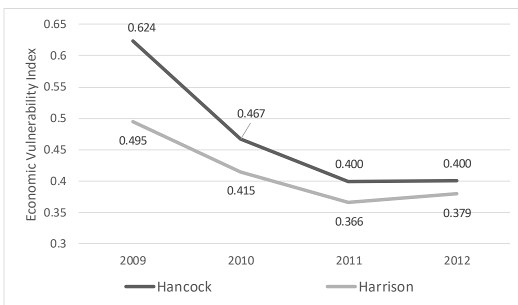


Figure 5: Proposed Model Outcome Social vulnerability.

5.3 Economic vulnerability

Figure 6 presents the existing economic vulnerability per county. Figures 7 and 8 illustrate the economic vulnerability utilizing the actual budget simulation and the proposed model, respectively. It can be observed that the proposed model did not provide significant reduction in economic vulnerability compared to the actual budget distribution. This is due to the complex multi-dimensional optimization utilizing PFS carried out at the government level that provided a compromise optimal solution across the different objective functions. However, it can be observed that the learning module reacted when noticing a low rate in decreasing the economic vulnerability (2009-2010), and increased the rate of vulnerability reduction by 2010-2011.



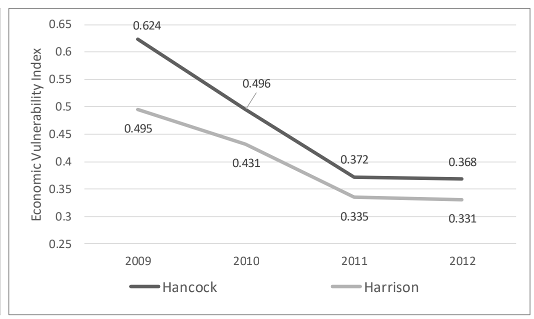


Figure 6: Existing Economic Vulnerability

Figure 7: Actual Budget Distribution Economic Vulnerability

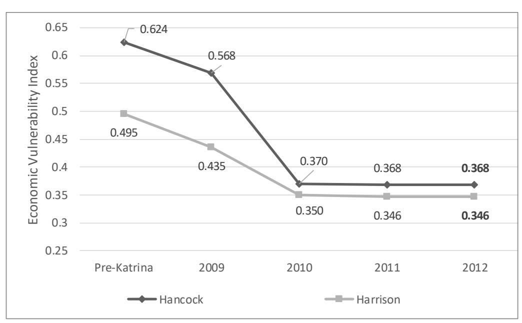


Figure 8: Proposed Model Outcome Economic vulnerability

5.4 Environmental vulnerability

Figure 9 illustrates the existing environmental vulnerability per county. The actual budget distribution scenario did not provide the same values for the existing conditions due to the limitation in modeling the environmental variables within the host community. As shown in Figure 10 and 11, the proposed model dominated the actual budget distribution across the two counties, due to the integration of the environmental vulnerability indicator into the government decision making process, such global reduction in environmental vulnerability scores was developed. The proposed model impact can be noticed in the most populated county, Harrison, where the EVI scores reached only 3.791, in comparison to 3.85. The proposed model also utilized other infrastructure projects to address the environmental vulnerability of the communities, but they are not within this paper scope. For further information, see Eid and El-adaway (2016a).

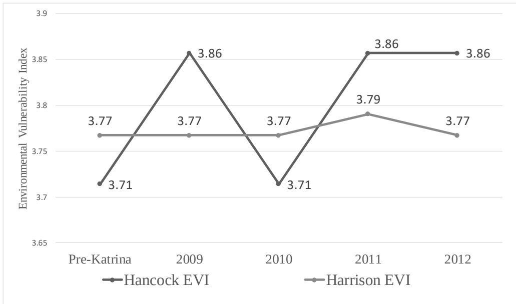


Figure 9: Existing Environmental Vulnerability

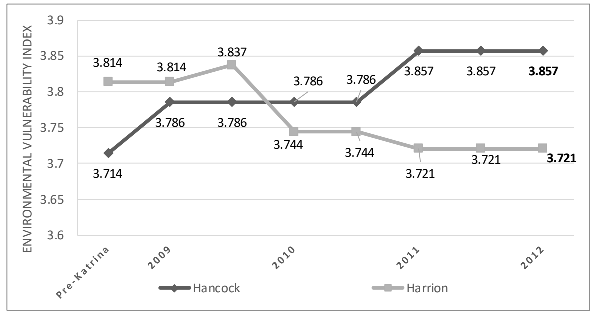


Figure 10: Actual Budget Environmental Vulnerability

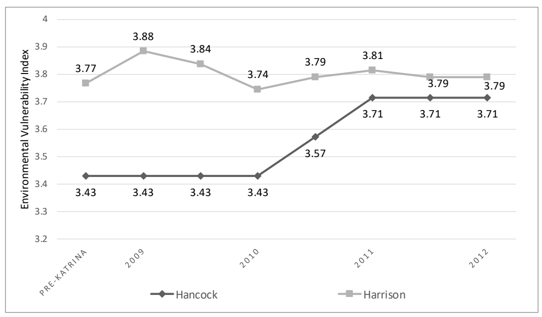


Figure 11: Proposed Model Outcome Environmental Vulnerability

5.5 Residential recovery

The proposed approach impact on the residential sector recovery is illustrated within this section. It can be seen through the residential recovery, Figures 12-13, that the proposed model dominated the actual budget distribution scenario both through the recovery rate and the total residential recovery. This is due to the integration of the utility functions of the residents within the objective functions of the government agent that guided the budget distribution to meet the needs of the different residents. The proposed model utilized the Public Home Assistance to meet the needs of double the number of residents in comparison to the actual budget distribution. The proposed model also increased the share of Elevation Grant that increased the number of benefactors to four folds that eventually increased the overall residential recovery. Such plan utilizes more resources to increase the household resilience and value, thus it increased the residential recovery to more than 100%.

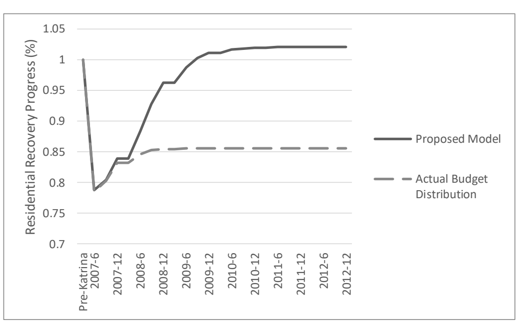


Figure 12: Hancock County Residential Recovery

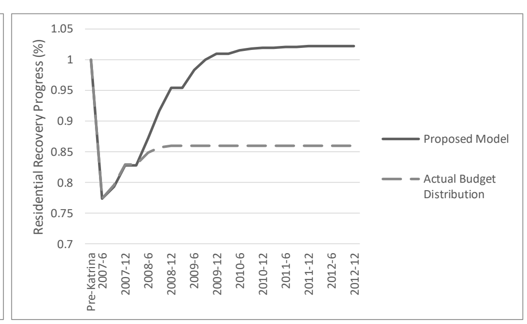
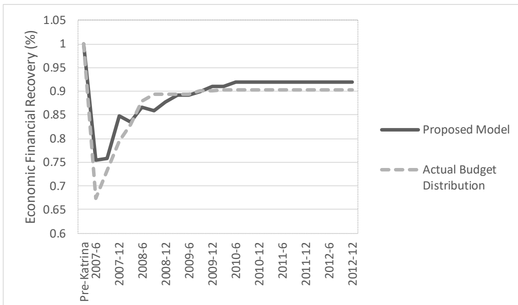


Figure 13: Harrison County Residential Recovery

5.6 Economic recovery

This section evaluates how the proposed framework impacted the financial recovery of the economic sector within the impacted region. A comparison between the outcomes of the developed model and the actual budget distribution is illustrated in Figures 14-15. Due to the utilization of the Small Business Loan, the proposed model incentivized the economic sector to remain in the community. This is noticed in the overall recovery rate across the two counties. The model also provided higher overall financial recovery in comparison to the actual budget distribution. This is contributed to the utilization of the different residential recovery plans that impact the revenue of the economic sector (Eid and El-adaway 2016b).



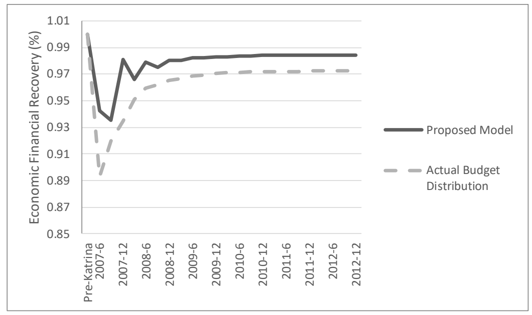


Figure 14: Hancock County Economic Recovery Figure 15: Harrison County Economic Recovery

6 CONCLUSION AND FUTUREWORK

The presented paper proposed a decision-making framework for holistic sustainable disaster recovery. The framework utilizes a bottom-up modeling approach to assimilate the needs of the residential and economic sectors while accounting for the vulnerability of the host community. The framework makes use of comprehensive well-established vulnerability indicators that guide the redevelopment strategies through integrating them into the objective functions of the government agent. The model was implemented on the post-Katrina recovery in two coastal counties in Mississippi. The model was able to determine optimal budget distribution for the government agent that increased the recovery rate of the residential and economic sectors, while reducing the social, economic, and environmental vulnerability of the built environment. Such novel approach will enable the decision makers to engage their communities in the prevent-event phases to find the common shared goals that decrease the built environment vulnerability and achieve true sustainability post a disastrous event. The proposed framework assumed that the disaster recovery strategies have deterministic outcomes. Accordingly, the developed framework can be improved through accounting for the stochastic nature of the recovery activities. The authors will also consider the different modeling limitations that constrained the current framework; vegetation cover re-growing parameters, new residents entering the impacted region, etc. The proposed model will also account for the social learning among the resident agents to accurately depict the complex interrelationship between the stakeholders and the redevelopment processes.

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